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ROLE OF DIFFERENTIAL FRICTION AND ASYMMETRY OF THE TOTAL FLOW ON HURRICANE MOVEMENT

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ABSTRACT

Under elementary considerations the vorticity changes induced by differential friction and asymmetry of the the combined hurricane and large-scale flows were incorporated in the prediction equation and integrated with a view to forecasting the movement of hurricanes. After determining the difference between frictional and frictionless forecasts based upon idealized data, seven 24-hr and four 48-hr frictional and frictionless forecasts of the movement of hurricane Cleo, 1964, were obtained. Introduction of surface friction resulted in improved 24-hr directions of movement and reduced the magnitude of vector error in the 48-hr displacement. Causes underlying the observed improvement were analyzed.

1. INTRODUCTION

The purpose of this investigation is to examine the combined role of differential surface friction and the departure of the total flow from circular symmetry in the predicted movement of a hurricane. The total flow represents the combined hurricane circulation and steering current.

The complex manner in which the atmospheric boundary-layer flow influences hurricane movement and intensification may ultimately be understood only with the assistance of a sophisticated multilevel numerical model. However, the way in which both the differential friction and asymmetrical characteristics of the motion field influence the movement of a hurricane when it is close to a landmass can be usefully studied by employing a simple barotropic model, a model in which surface friction affects the evolution of the hurricane flow by causing vorticity changes. In the following study, both analytical and real data were used to produce forecasts. With hypothetical data it is comparatively easy to isolate the frictional effect, while with real data the general accuracy of the forecasts and the relative performance of the frictional and frictionless models can be determined.

The total flow method (Birchfield, 1960) with a local fine grid was employed to make a 12-hr forecast with analytical data and a set of seven 24-hr and four 48-hr barotropic forecasts of hurricane Cleo (1964) with data gathered at the surface and at 700 mb.

2. THE PREDICTION MODEL

The potential vorticity equation with frictionally induced vertical motion (Cressman, 1960) is the prediction equation and can be written, with the usual notation as

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$$(\partial/\partial t)(\nabla^2-\lambda^2)\psi=J(\nabla^2\psi+f,\psi)+\omega_F f_0/(p_g-p_t)$$

where

$$\omega_F=g\rho f_0^{-1}\left(\frac{\partial}{\partial y}(C_d u_s|\mathbb{V}_s|)-\frac{\partial}{\partial x}(C_d v_s|\mathbb{V}_s|)\right)\text{ and }\lambda=(gD_0)^{-1/2}f_0. \quad (1)$$

In the above, f_0, and D_0 are, respectively, the mean values of f (the Coriolis parameter) and D, the depth of the atmosphere at rest. The quantity ψ is the stream function describing the nondivergent part of the velocity field, while u_s and v_s are the horizontal components of the surface wind vector $\mathbb{V}_s$. The frictionally induced vertical velocity, ω_F, is dependent upon the surface drag coefficient, C_d, the relative vorticity of the flow, and the general motion field configuration. The pressures at the ground and at the tropopause are, respectively, p_g and p_t. Regions with cyclonic vorticity are marked by ascending motion at the top of the friction layer. A compensating divergence field that exists above the friction layer is responsible for the reduction of cyclonic vorticity. With equal nonzero drag coefficients, two areas with different vorticity amounts would suffer nonuniform vorticity changes. Similarly, with equal relative vorticities, air in contact with a rougher surface experiences more ascending motion and consequently a decrease in vorticity at a faster rate than that in contact with a smoother surface.

Recently, Kasahara and Platzman (1963) discussed the two basic "total-flow" and "steering-flow" methods of adopting the potential vorticity equation to predict the trajectory of a hurricane. Both methods are designed to solve the problem of dealing with two different scales of motion encountered in hurricane prediction. In the total-flow method, the hurricane is retained as an integral part of the predicted flow. By employing a fine grid locally over the hurricane circulation (Birchfield, 1960) or over the whole map (Birchfield, 1961; Sanders and Burpee, 1968), truncation errors are reduced to such an extent that some characteristic features of the hurricane circulation are represented fairly well. Because of its directness, this method with a local fine grid was used.

3. NUMERICAL INTEGRATION WITH ANALYTICAL DATA AND RESULTS

Figure 1 shows part of the coarse grid and a position of the fine grid. Grid intervals on these lattices are, respectively, 250 km and 100 km. For the purpose of forecasting with hypothetical data, it was supposed that the coarse grid points on the rows 1 through 12 represent smooth land with a drag coefficient of 0.0020, and the rows 13 through 20 represent ocean with a coefficient of 0.0015. Generation of initial stream functions took place in three steps. First, assuming a zonal westerly wind profile, stream functions on the coarse grid (ψ_c's) were derived. Second, assuming that the hurricane scale circulation was adequately covered by the fine grid centered on the storm, stream functions on the fine grid (ψ_f's) were produced. Finally, the total stream-function field at 700 mb over the fine grid was found by linearly interpolating ψ_c's over the fine grid and combining them with ψ_f's. The ψ_f's were developed from Vanderman's formulas (1962) assuming a maximum tangential motion, v_m, of 40 m sec^{-1} at the edge of the eye, a distance R_0 from the center of the storm, and setting ψ_f, a distance R from the center, to be zero. With $R_0=100$ km and $R=1000$ km, these analytical formulas are

$$\psi_{1_f}(r)=v_m(2R_0)^{-1}(r^2-R_0^2)+\psi_{2_f}(R_0) \quad 0<r<R_0$$

and

$$\psi_{2_f}(r)=\tfrac{8}{3}v_m(r^{3/8}-R^{3/8})R_0^{5/8} \quad R_0<r<R \qquad (2)$$

where $r^2=x^2+y^2$, x and y being the Cartesian distances of a point from the center.

Table 1 shows the initial ψ_c's describing a wind field having two westerly maxima of about 10 m sec^{-1} and 9 m sec^{-1} just south of rows 8 and 13, respectively. In spite of its simplicity, an initially linear westerly current over the coarse grid was not employed because in the vicinity of the hurricane a nearly symmetrical vertical motion field resulted that looked unlike the asymmetrical field characteristic of real data (Izawa, 1964).

With time steps of integration as 1 hr on the coarse grid and as 10 min on the fine grid, forecasts with friction were made in a manner similar to Cressman (1960). On the fine grid, the surface winds over the 121 points surrounding the hurricane center were approximated by 80 percent of the winds at 700 mb. (See Hubert, 1955, on the validity of this approximation.) At the boundaries of the fine grid and over the large grid, surface winds were estimated to be 40 percent of the 700-mb winds.

Using 1630 km as the inverse of λ (Kasahara and Platzman, 1963) and equation (1) on the coarse grid, the relative vorticity was extrapolated in the standard manner from t to t plus 1 hr. Boundary ψ_c's were not permitted to vary with time, and existence of the fine grid was disregarded in this 1-hr time extrapolation. Boundary ψ_f's were computed from the t and t plus 1 hr ψ_c's by interpolating linearly in time and in space. By performing six 10-min time steps, equation (1) was integrated over the fine grid. Evolution of the flow in the fine grid was incorporated into that of the coarse grid by replacing the ψ_c's by the values from the fine-grid time extrapolations.

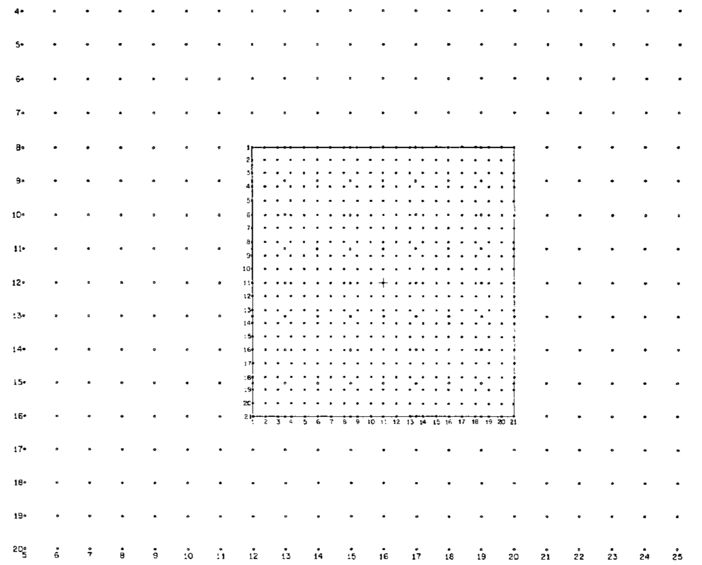

FIGURE 1.—Part of the coarse grid with a typical position of the fine grid; grid distance, 250 km on the coarse grid; note row and column numbers.

For a control, using Cressman's (1960) zonal wind profile, a 72-hr frictionless forecast employing equation (1) was made. A maximum change of 1.2×10^{11} cm^2 sec^{-1} in the stream function resulted at a certain point. A 24-hr frictional forecast revealed a change of nearly twice this magnitude at the same point. This is certain evidence that significant effects were introduced by the inclusion of friction.

The total flow due to our choice of ψ_c's has vortical asymmetry with respect to the center of the storm being more cyclonic to the right of direction of movement than to the left. Due to this fact and the nonlinearity of the frictional stress, more ascending motion is frictionally induced to the right than to the left. Based on the prescribed C_d-distribution alone, however, more ascending motion should result to the left with reference to the vortex center than to the right. Although considerable inaccuracy lies in the assumed C_d's, the employment of reasonable values revealed that the asymmetry of the total flow was more contributory to the nonuniform nature of the vertical motion field than the differential distribution of drag.

Table 2 shows the initial total stream functions in the vicinity of the vortex center. For reasons explained in the next section, a point midway between the minimum stream function and maximum vorticity in the forecast total stream function was defined as the center of the

TABLE 1.—*Meridional distribution of initial stream functions ψ_c's on the coarse grid. Units: 10^9 cm ^{2} sec^{-1} with minus sign omitted*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
229	227	224	220	212	200	182	158	133	109	94	89	74	51	30	14	4	−.6	−1.8	0

TABLE 2.—*Initial total stream functions close to hurricane center. Units: 10^9 cm^2 sec^{-1} with minus sign omitted*

Row \ Column	9	10	11	12	13
9	189	202	208	202	189
10	200	222	237	222	200
11	203	235	255	235	203
12	191	214	229	214	191
13	172	185	191	185	172

TABLE 3.—*Twelve-hour predicted total stream function close to hurricane center. Units: 10^9 cm^2 sec^{-1} with minus sign omitted. Figures within and without parentheses are, respectively, those with and without friction.*

Row \ Column	10	11	12	13	14
10	187(179)	205(196)	226(214)	234(221)	219(208)
11	177(171)	205(196)	239(226)	246(230)	225(212)
12	165(161)	196(188)	230(216)	235(218)	212(199)
13	153(150)	170(164)	193(182)	197(185)	185(175)
14	140(138)	149(145)	157(152)	161(154)	156(149)

storm. This was located objectively using an inverse linear interpolation technique. From table 3, one finds that this center in the frictional and frictionless cases moved, in a generally east-southeasterly direction, respective distances in 12 hr of 152 km from 277°55′ and 158 km from 281°38′. It is believed that, although the magnitude of the deviation is not very large, the sense of deflection, i.e., the leftwardness of the frictional forecast in relation to the frictionless case caused by the stronger ascending motion to the right of direction of movement, is of practical significance.

4. NUMERICAL INTEGRATION WITH REAL DATA AND RESULTS

Surface and 700-mb maps were prepared at 00 and 12 GMT for the period Aug. 25 through Aug. 30, 1964, and were subjectively analyzed by Mr. C. L. Smith of the National Hurricane Research Laboratory. Figure 2 provides an idea of a Lambert conformal map on which the meteorological observations were plotted and analyzed.

The fine grid was placed so that its central point coincided with the reported position of the hurricane, and heights were read over both the large and fine grids. Balanced ψ_c's on the coarse grid were obtained in a manner similar to Bolin (1956) and Shuman (1957*a*). Through linear interpolation from the coarse grid, the balanced ψ_f's on the boundary of the fine grid were obtained. By utilizing these boundary values, balanced ψ_f's on the fine grid were determined.

Surrounding the hurricane, the balanced ψ_f's at 120 points on the fine grid were altered (adapting a procedure by Jones, 1964) in such a way that they yielded at the storm center point a velocity with which the hurricane moved during the past 12 hr. This past movement was deduced from the "best track" of the hurricane. Adaptation of Jones' procedure was meant merely to obtain an improved, initial total-flow field in the vicinity of the hurricane. As stated earlier, our prediction is based on the total-flow method as distinct from the steering-flow method which Jones used. The ψ_c's were replaced by those from the fine grid at the common points.

Boundary ψ_c's were permitted to vary with time. Since this study was performed in a research environment, this was accomplished by analyzing the height field for the various map times covering the range of the forecast period reported here.

Drag coefficients over land were obtained from Cressman (1960). In the process of interpolation, however, no value less than 0.0018 was utilized. Oceanic points received a drag coefficient of 0.0015.

To remove any possible irregularities in the ψ_c-field close to the boundary of the fine grid, ψ_c's were smoothed at intervals of 6 hr using Shuman's nine-point operator (1957*b*).

If at any time during the forecast interval the minimum stream function moved away from the eight points surrounding its original position on the coarse grid, a subroutine was initiated that moved the fine grid so that it was approximately over the center of the storm.

Following the earlier integration procedure, seven 24-hr forecasts for the period August 25 through 28 and four 48-hr forecasts for August 26, 27, and 28 were made. Prior to presenting detailed analyses of these forecasts it is necessary to discuss the choice of the predicted center of the hurricane. Points of minimum stream function were not identifiable for all 24-, 36-, and 48-hr durations for all map times. These points, however, could be located for all 12-hr forecasts.

The center of the hurricane in this study for 24-hr and 48-hr forecasts was defined as the predicted point of maximum vorticity obtained by linear inverse interpolation. For the 12-hr forecasts, a point midway between the positions of minimum stream function and maximum

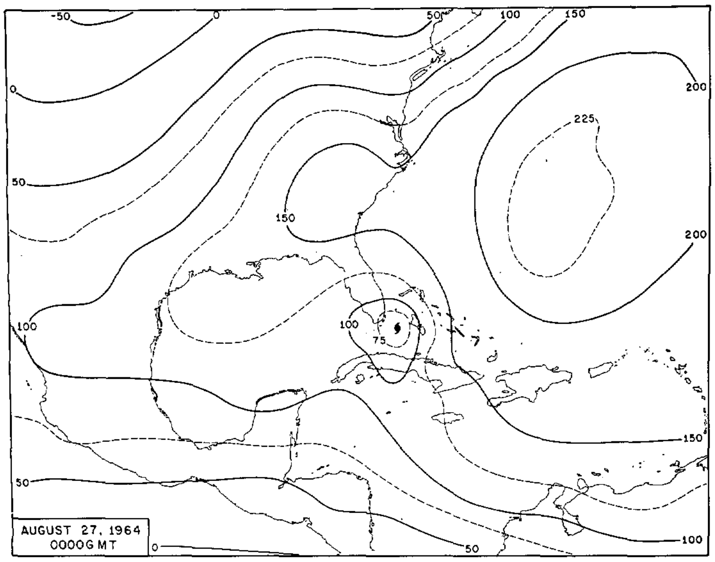

FIGURE 2.—Balanced stream functions, ψ_c's, modified adjacent to the hurricane, in units of 10^9 cm^2 sec^{-1} obtained from the observed z-field at 700 mb.

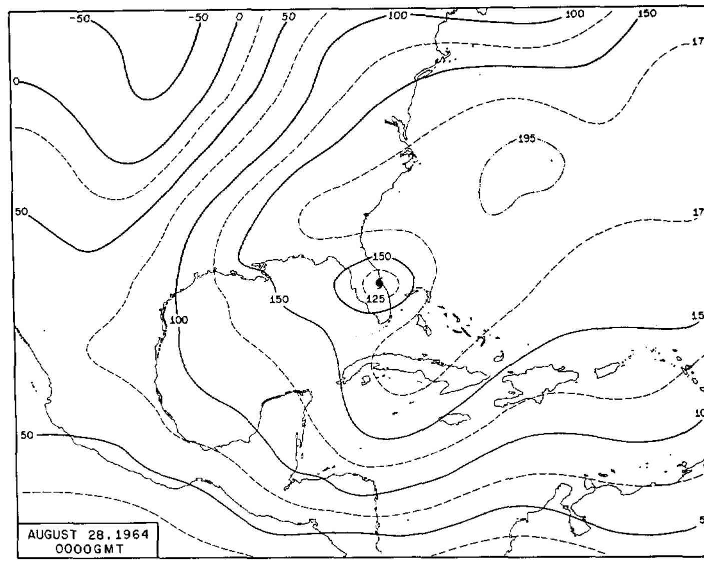

FIGURE 3.—Same as figure 2.

vorticity was defined as the center. The rightward angular deviations of 24- and 48-hr predicted positions with respect to observed positions would have been reduced had we chosen the point of minimum stream function (or, a point midway between minimum stream function and maximum vorticity) to represent the hurricane. For example, at two initial map times (August 27, 12 GMT, and August 28, 00 GMT) when 24-hr stream function minima were identifiable, the average angular deviation was reduced by 5° on the basis of two forecasts with friction and two without friction.

The following will be a discussion of a typical 24-hr forecast with and without friction verifying at August 28, 00 GMT. Figures 2 and 3 show the observed fields analyzed in terms of stream function.

Noteworthy features of figure 2 are the trough over western North America, the Bermuda anticylcone and its extension over the southeastern United States, and hurricane Cleo situated south of Florida. The observed field in terms of stream function 24 hr later, as shown in figure 3, indicates that the trough in the westerlies deepened considerably, the Atlantic anticyclone moved to a position approximately 1000 km west of Bermuda, while hurricane Cleo described a course paralleling the east coast of Florida.

The 24-hr prediction maps, figures 4 and 5, show that the deepening of the extratropical trough was not well forecast. Also, in regard to the Bermuda anticylcone more intensification was predicted than actually took place. The direction of movement of Cleo was reasonably well forecast even though an overprediction of displacement occurred. The important difference between figures 4 and 5 is the slower movement of Cleo when friction was

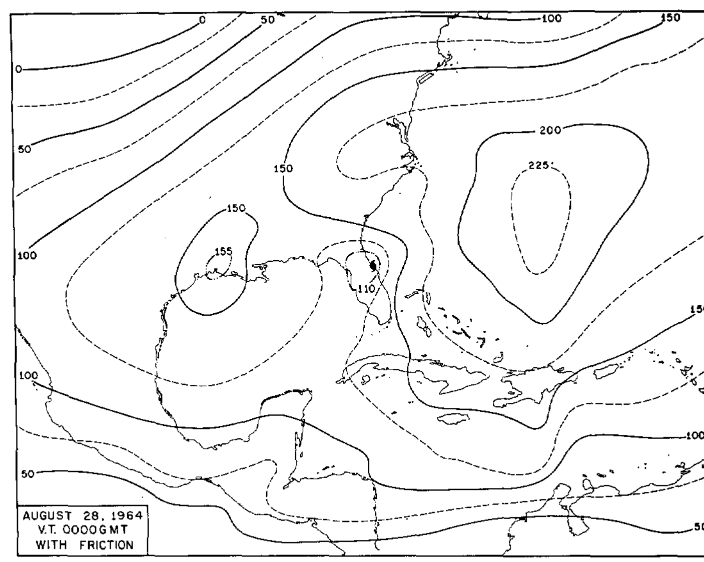

FIGURE 4.—Twenty-four-hour frictional forecasts with the initial data in figure 2.

included. Furthermore, the center of the hurricane in the former is to the left of the center in the latter.

Figures 6 through 9 show the observed and predicted movements of hurricane Cleo. On August 25, 12 GMT, while over southeastern Cuba, the storm began a pronounced northwesterly movement. Two days later it entered the southeast coast of Florida and subsequently remained a small distance inland while traveling the length of Florida, gradually losing hurricane intensity.

Even though the 24-hr predicted displacements in figures 6 and 8 were a little less than those in figures 7 and 9, the angular deviation of the predicted from the observed in the former were less than those in the latter. In figure 10 are

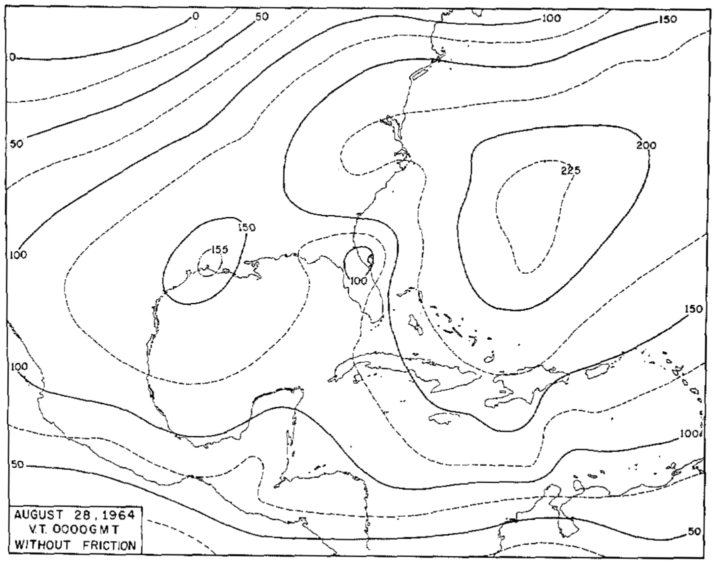

FIGURE 5.—Twenty-four-hour frictionless forecast with the initial data in figure 2.

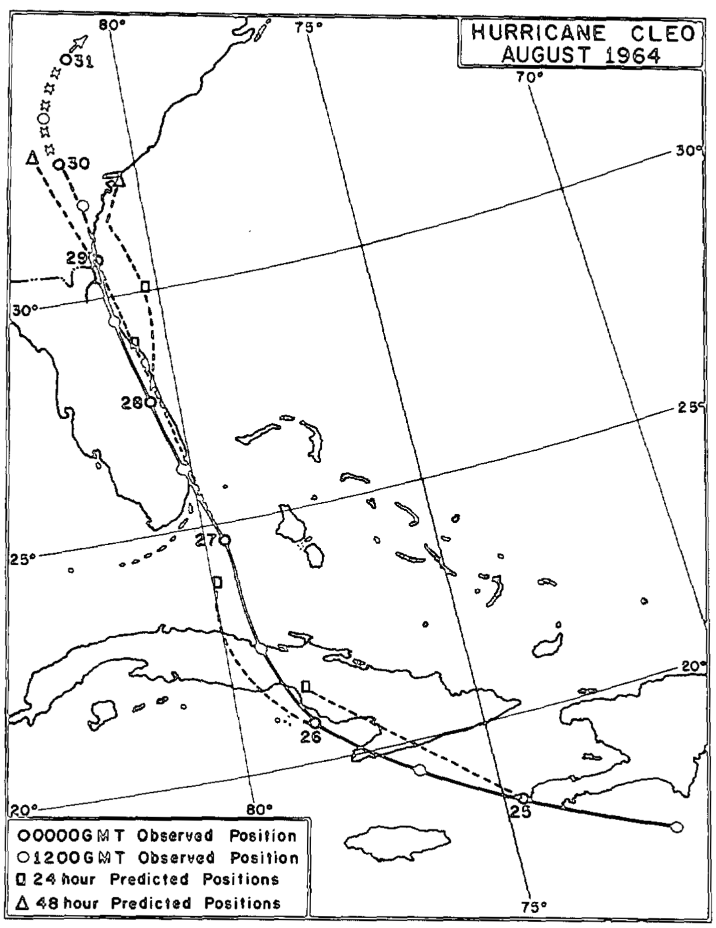

FIGURE 6.—Observed and predicted 24-hr and 48-hr 700-mb positions for hurricane Cleo, August 1964, with friction based on 00 GMT data.

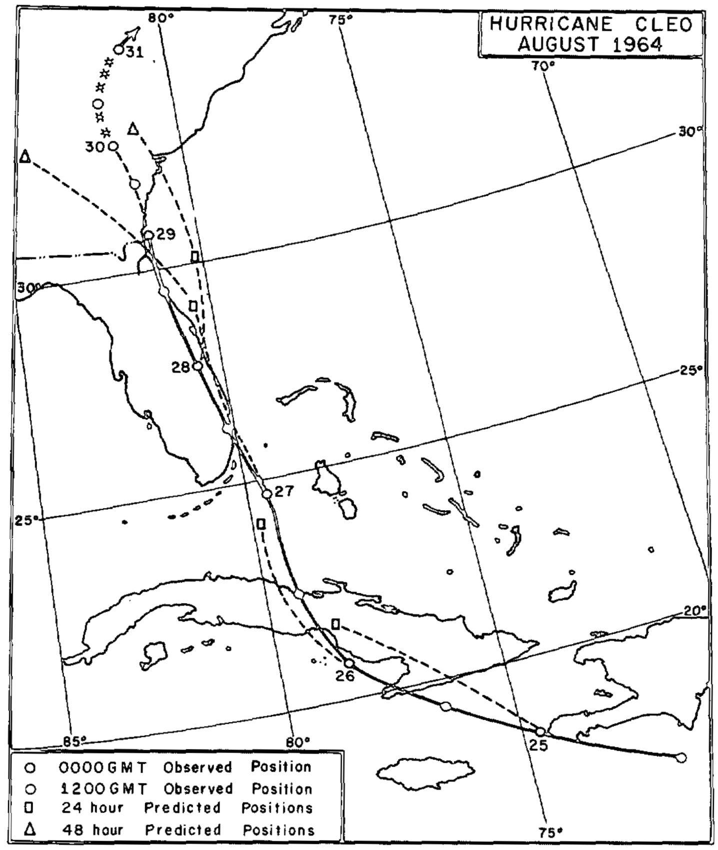

FIGURE 7.—Observed and predicted 24-hr and 48-hr 700-mb positions without friction for hurricane Cleo, August 1964, based on 00 GMT data.

shown the centroids of scaled 24-hr displacement vectors constructed following Kasahara and Platzman (1963). Each centroid was obtained using seven forecasts. The circle with its radius equal to the average magnitude of deviations of scaled vectors from their mean is a measure of the dispersion of the seven predicted points. A noteworthy feature of this figure is the improvement in the predicted direction of motion with friction. The mean angular rightward deviation of the 24-hr forecast displacement vector from the observed displacement vector with friction was 9° 24′ and without friction 12° 35′.

Table 4 lists the details of the seven 24-hr forecasts with the magnitudes of vector error E_f and E_n, with friction and without friction, respectively. Average $\overline{E}_f$ was less than $\overline{E}_n$, although the difference was only 0.5 n.mi. The statistics presented by Miller and Gentry (1967) reveal how our average 24-hr forecast shown in table 4 compares with the U.S. Weather Bureau official operational average forecast. According to them, a mean error of 116 n.mi. occurs in the 24-hr official predictions made during the years 1959–66. Our average vector error of about 62 n.mi. compares favorably.

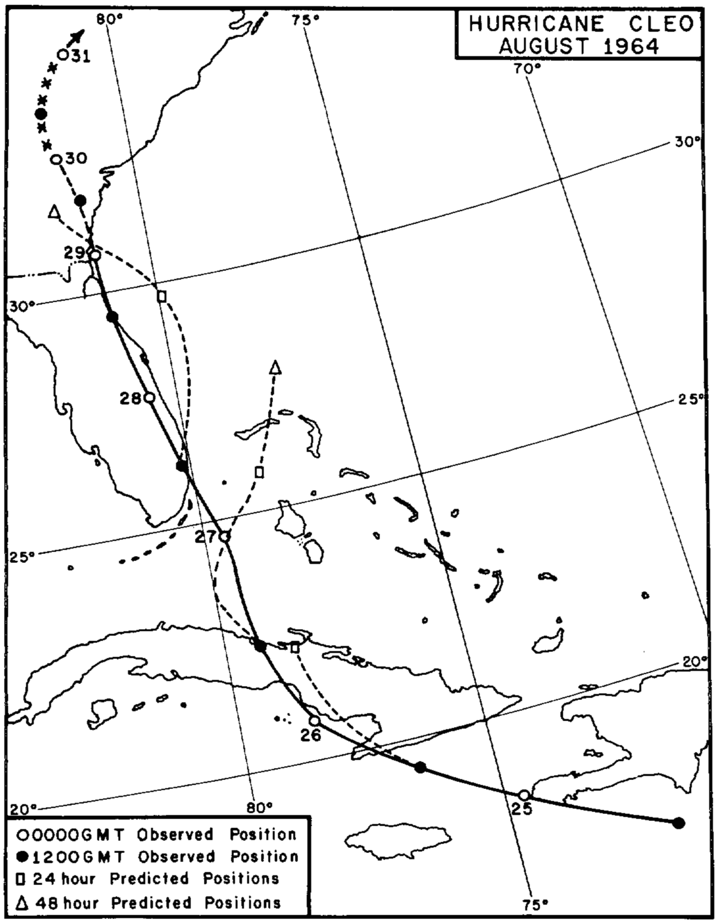

FIGURE 8.—Observed and predicted 24-hr and 48-hr 700-mb positions with friction for hurricane Cleo, August 1964, based on 12 GMT data.

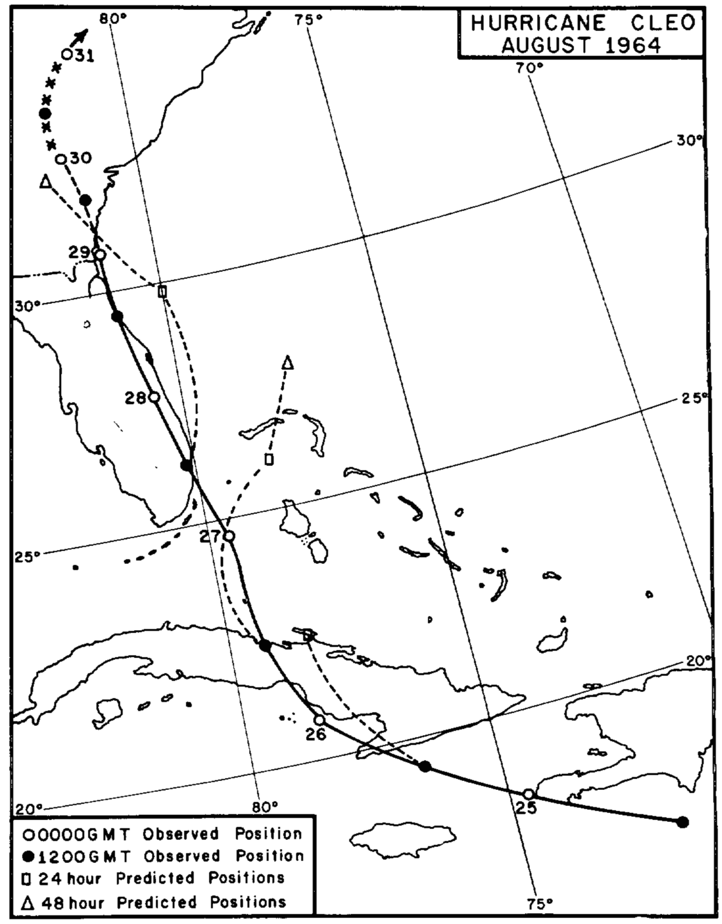

FIGURE 9.—Observed and predicted 24-hr and 48-hr positions without friction for hurricane Cleo, August 1964, based on 12 GMT data.

It is also of interest to examine the performance of this technique relative to that of the other techniques for each map time, realizing that it may be inappropriate to compare the operational forecasts with predictions developed in a research environment. Such a comparison is made simply to determine how far the current model produced acceptable results. The last two columns of table 4 show the magnitudes of vector errors obtained using the two methods NHC–64 (National Hurricane Center 1964), and NWP (Numerical Weather Prediction). Details of these methods were discussed by Dunn, Gentry, and Lewis (1967). From the last four columns, it is clear that the current model produced promising results except on the last map time.

The mean magnitudes of vector error of 48-hr frictional and frictionless forecasts were 116 and 124 n.mi., respectively. Frictionless forecasts were characterized by larger vector errors. The tendency of the frictionless model to overpredict the displacement was responsible for this.

The leftward deviation of the frictional tracks mentioned earlier was caused by the asymmetry of the total flow along with friction. During the forecast period, hurricane circulation was partly over smooth land, but the drag coefficient characteristic of land and water did not differ much. On the other hand, the total flow showed considerable asymmetry, being stronger to the right of direction of movement than to the left. This asymmetry of the total flow was more contributory to the nonuniformity of the frictionally induced vertical motion field than the differential distribution of drag. The slightly larger ascending motions to the right of direction of motion caused a faster reduction of vorticity influencing the movement. Although uncertainty lies in the proper choice of drag coefficients and in determining the surface winds from the 700-mb winds, it was concluded that reasonable estimates of C_d's and $\mathbf{V}_s$'s were made since the frictionally induced vertical motions ω_F's in the model agreed favorably with those inferred by earlier investigators (e.g., Miller, 1964) in the lower layers.

The fact that frictional and frictionless predictions did not differ greatly suggests that within the framework of this simple forecast model the role of friction is only

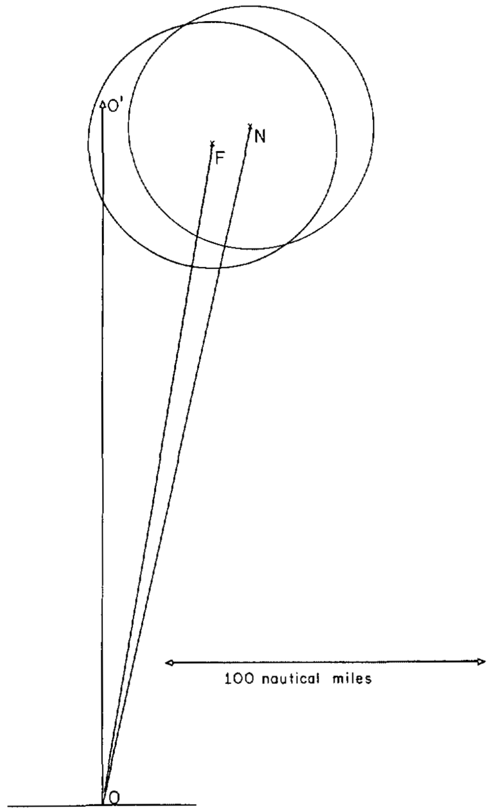

FIGURE 10.—Observed 24-hr average displacement vector of hurricane Cleo, August 1964, as shown by 00′; OF and ON represent the forecast displacement vectors with and without friction, respectively; the circles drawn with F and N as centers represent dispersion of vectors.

TABLE 4.—*Seven 24-hr forecasts; 24-hr observed displacement S_{ob}; 24-hr predicted displacements S_{pf} with friction and S_{pn} without friction; magnitudes of vector error E_f with friction and E_n without friction; E_{NHC-64} and E_{NWP} of the last two columns represent magnitudes of vector error under operational conditions. Units: nautical miles*

Forecast time	S_{ob}	S_{pf}	S_{pn}	E_f	E_n	E_{NHC-64}	E_{NWP}
25, 00 GMT	276	294	306	40	48	127	247
25, 12 GMT	243	210	213	42	48	100	72
26, 00 GMT	243	207	216	46	36	154	137
26, 12 GMT	246	210	222	96	98	111	185
27, 00 GMT	201	267	270	71	77	84	120
27, 12 GMT	204	201	207	65	60	missing	missing
28, 00 GMT	186	135	144	72	69	13	missing
Average	228	217	225	61.7	62.2	not taken	not taken

secondary. However, the average directional improvement in the 24-hr frictional predictions justifies the inclusion of friction. Such an improvement is particularly important when the hurricane comes close to populous coastal places.

5. SUMMARY

The potential vorticity equation with a simplified form of frictionally induced vorticity was numerically integrated, first with analytical data to obtain a 12-hr prediction of the motion of a vortex center, and then with the actual data of hurricane Cleo (1964) to obtain seven 24-hr and four 48-hr forecasts of the movement of its center. With idealized data the predicted movement in the frictional model was about 3°43′ to the left of that obtained with the frictionless model. The objective of integrating with analytical data was to demonstrate that a real difference between frictional and frictionless forecast exists. Frictionless forecasts of Cleo showed a rightward deviation from the actual direction of motion while frictional predictions exhibited a tendency to be on the left side of the frictionless predictions, thus agreeing favorably with the observed direction of movement. The systematic rightward deviation of predicted tracks using the steering-flow method was ascribed by Kasahara and Platzman (1963) to the inadequacy of the model to provide for the interaction between hurricane and large-scale flow. They showed by considering this interaction explicitly that the rightward deflection was greatly reduced. The current model, patterned after Birchfield's model (1960), allows for this interaction implicitly. Birchfield (1961) commented that this systematic rightward bias was significantly reduced in his predictions. Since the intent of this work was to find the role of differential friction and asymmetry of the motion field in the movement of a hurricane, the cause for the rightward deviation of the frictionless forecasts was not analyzed.

Examination of the total flow indicated that it was asymmetric with respect to the direction of movement with larger vorticity amounts to the right side. During most of the prediction period, nearly half of the circulation of the hurricane was over smooth land. In the model, the drag coefficients characteristic of smooth land and water did not differ much, and the asymmetry of the total flow was more contributory to the nonuniformity of the vertical motion field than the differential distribution of surface drag coefficients. The stronger ascending motions to the right caused faster reduction of vorticity amounts that eventually resulted in a leftward deflection of the storm center in the 24-hr forecasts. It is more evident in the 24-hr predictions than in the 48-hr predictions due to the weakening of the predicted circulation during the forecast interval. On the average, 48-hr frictional forecasts were marked by less vector error than the corresponding frictionless forecasts. Although, within the framework of this simple prediction model frictional and frictionless forecasts with real data did not differ greatly, the average improvement in the 24-hr predicted direction of movement with friction justifies the inclusion of friction in the model. Such an improvement is especially welcome when the hurricane comes close to densely populated areas.

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